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## High Redshift Galaxy Clusters as Probes of Cosmology

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**Abstract.** A few, simple and qualitative examples of the potential of galaxy clusters as diagnostics of cosmology are presented. In relation to these we discuss briefly three ongoing or forthcoming cluster surveys in the optical/NIR, X-rays and the cosmic microwave radiation background.

### 1. Introduction

There is continuing evidence that the first Doppler peak in the angular power spectrum of the Cosmic Microwave Background (CMB) is located at multipole number  $l \sim 200$ . This suggests that the Universe is flat (or, at least, nearly flat) consistent with the predictions of standard inflationary theories that  $\Omega_{tot} = 1$  (de Bernardis et al. 2000, Hanany et al. 2000). Moreover, the results of recent intermediate redshift supernova type Ia (SNIa) surveys indicate that the cosmological constant is non-zero (Riess et al. 1998, Perlmutter et al. 1999). Taken together, the above results indicate that  $(\Omega_M, \Omega_\Lambda) \sim (0.3, 0.7)$ , where  $\Omega_M$  is the present matter density parameter and  $\Omega_\Lambda$  is the density parameter corresponding to the cosmological constant  $\Lambda$ .

The interpretations given above of the observational results are, of course, a matter of debate: if recombination is delayed due to, e.g., sources of Ly $\alpha$  resonance radiation, such as stars or active galactic nuclei (Peebles et al. 2000), or slow decay of dark matter (Doroshkevich & Naselsky 2000, Naselsky et al. 2001) the observed position of the first Doppler peak may actually indicate that the Universe is open (Peebles et al. 2000). Furthermore, SNIa may not be standard candles and effects of dust absorption (like a redshift dependent extinction law) may not have been properly accounted for (S. Toft, private communication). These complications could affect the determinations of  $\Omega_M$  and  $\Omega_\Lambda$  from the CMB and SNIa results.

Clearly, completely independent ways of determining  $\Omega_M$  and  $\Omega_\Lambda$  are highly desirable. One such way is to observationally determine the mass function of galaxy clusters at present as well as at redshifts up to  $z \sim 1 - 2$ :

### 2. High redshift clusters as probes of cosmology

The observed present-day abundance of clusters places a strong constraint on cosmology:  $\sigma_8 \Omega_M^{1/2} \simeq 0.5$ , where  $\sigma_8$  is the *rms* mass fluctuations on  $8 h^{-1}$  Mpc scale - see, e.g., Eke et al. 1996 ( $h$  is the present Hubble parameter in units of 100 km/s/Mpc; the above constraint also depends weakly on  $\Omega_\Lambda$ ). This constraint

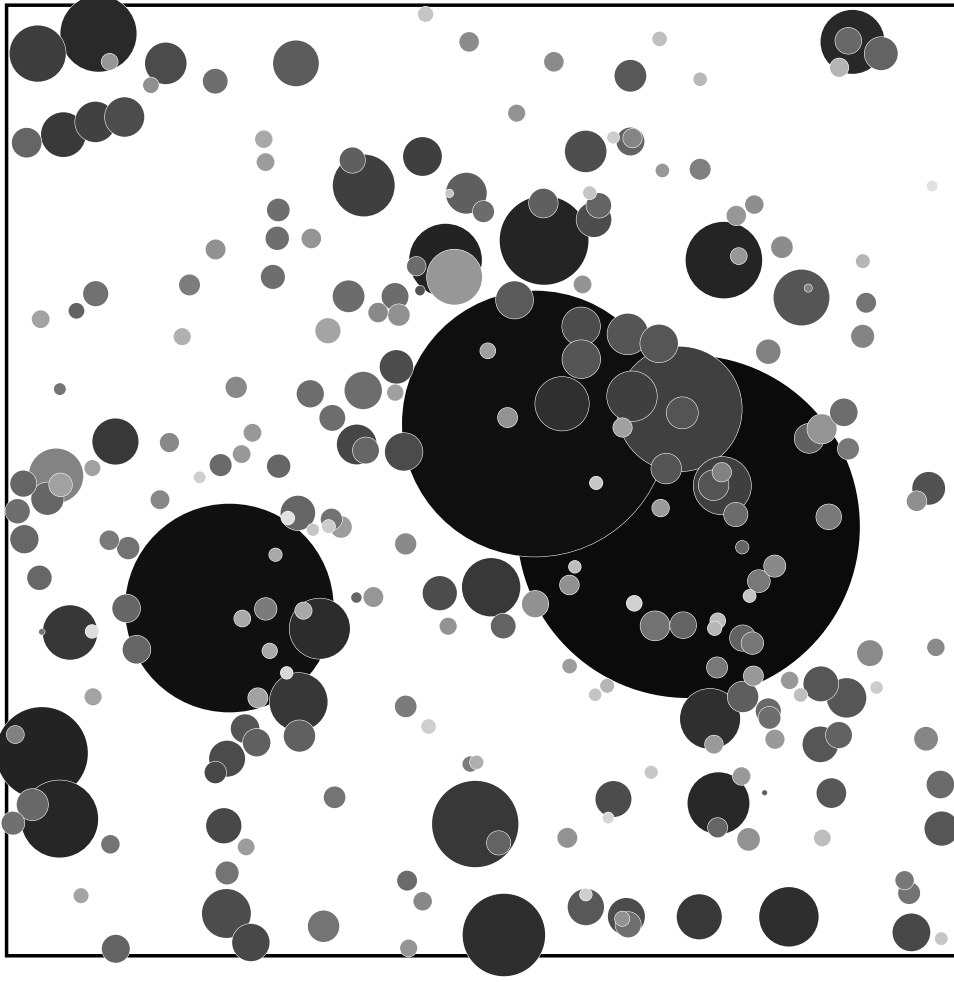


Figure 1. The 247 clusters with  $M \geq 10^{14} M_{\odot}$  and  $0 < z \leq 1.4$  in a  $2.9 \times 2.9 \text{ deg}^2$  pencil beam (almost) randomly selected from a SCDM simulation. The grey-scale coding is such that brightness increases with redshift - see text for details.

is degenerate in  $\Omega_M$  and  $\sigma_8$ , but the degeneracy can be broken by studying the evolution of cluster abundance with redshift, especially for massive clusters - see, e.g., Borgani & Guzzo (2001) and references therein. To illustrate this in a qualitative way we show in Figures 1 and 2 the appearance on the sky of clusters at redshifts  $0 < z \leq 1.4$  in a (almost) randomly selected  $2.9 \times 2.9 \text{ deg}^2$  pencil beam for a SCDM and a  $\Lambda$ CDM cosmology (with  $(\Omega_M, \Omega_{\Lambda}, h, \sigma_8) = (1.0, 0.0, 0.5, 0.53)$  and  $(0.3, 0.7, 0.65, 1.0)$  respectively). The pencil beam was selected from N-body simulations, which are effectively  $\sim 2 \cdot 10^{10}$  particle, “Hubble volume” simulations. All clusters with mass  $M \geq 10^{14} M_{\odot}$  are shown by filled circles with radius equal to the apparent virial radius and grey-scale coding such that brightness increases with redshift. The difference between the two figures is striking, and for the  $\Lambda$ CDM cosmology the cluster sky covering fraction appears to be  $\gtrsim 30\%$  out to a redshift of 1.4 and hence even larger than the otherwise impressive

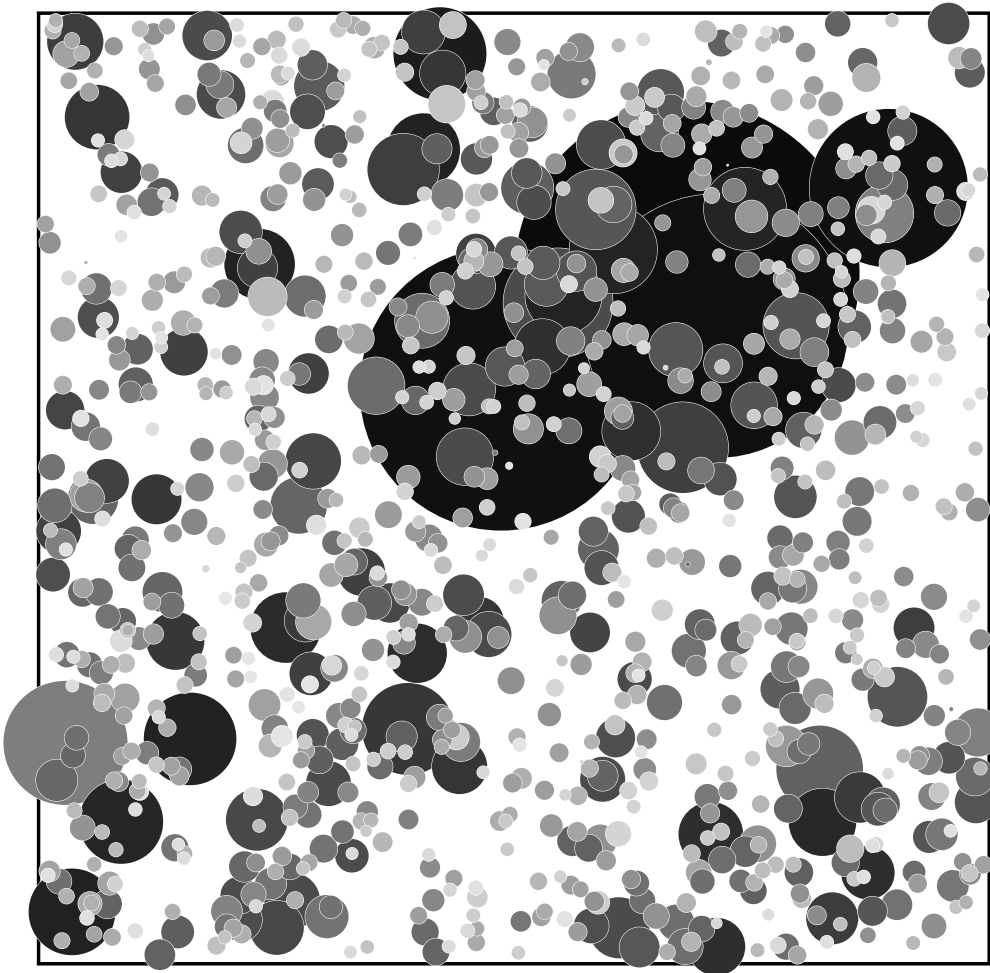


Figure 2. Same pencil beam as in Figure 1, but for a  $\Lambda$ CDM simulation, showing the 1016 clusters with  $M \geq 10^{14} M_{\odot}$  and  $0 < z \leq 1.4$ .

$\sim 20\%$  for the damped  $\text{Ly}\alpha$  systems to redshifts of 4-5 (one might argue, though, that for detection in X-rays or optical/NIR it would be reasonable to use  $r_{500}$ , rather than the virial radius - this would reduce the cluster sky covering fraction by almost a factor of 4 for the  $\Lambda$ CDM model).

The determination of  $\Omega_M$  and  $\Omega_{\Lambda}$  using clusters requires fairly large cluster surveys ideally out to redshifts of  $z \sim 1.5$ -2 - see below. The Copenhagen cluster group is involved in three such surveys: 1) The ESO Imaging Survey (EIS), which is an optical/NIR survey covering, when completed,  $15 \text{ deg}^2$ , 2) The XMM-Newton Large Scale Survey (XMM-LSS), which is an X-ray survey covering, when completed,  $64 \text{ deg}^2$ , and finally 3) The Planck thermal Sunyaev-Zeldovich (tSZ) all sky cluster survey (more information about the surveys etc. is available at our web site <http://www.astro.ku.dk/xcosmos>).

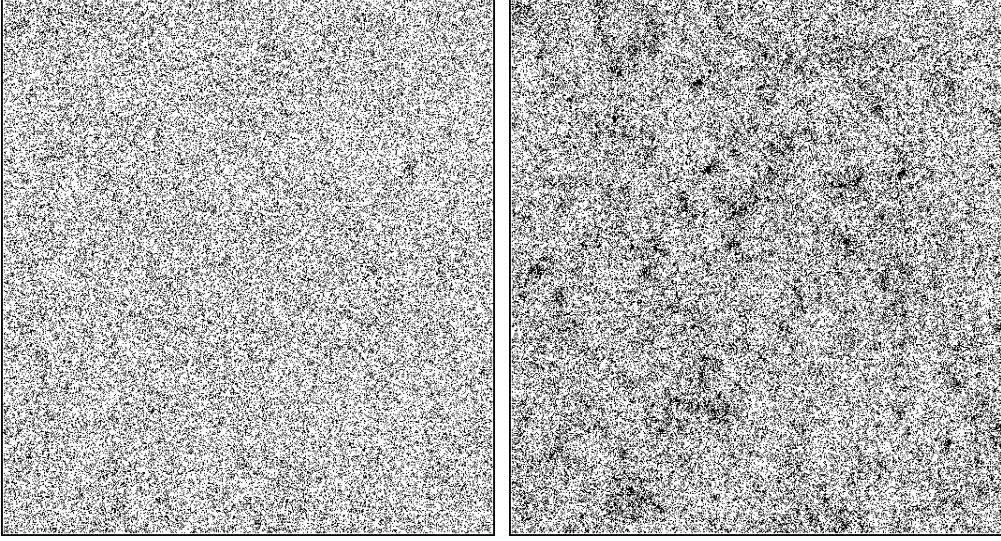


Figure 3. A simplified visualization of the predicted “observed” galaxy distributions corresponding to Figures 1 (left panel) and 2 (right panel), assuming (for simplicity) a passively evolving field galaxy luminosity function to represent the galaxy distribution everywhere and an apparent magnitude range of  $12 < m < 24$ .

### 2.1. Optical/NIR

To qualitatively illustrate the potential difficulties in optical/NIR cluster searches we made the following little experiment: At the position of each of the  $\sim 10^7$  dark matter particles in the pencil beams shown in Figures 1 and 2 we randomly drew from an appropriately normalized, passively evolving field galaxy luminosity function (LF). If the apparent magnitude of the “galaxy” drawn was between 12 and 24 (the approximate magnitude limits of the EIS survey) a point was plotted in Figure 3 (SCDM: left panel,  $\Lambda$ CDM: right panel). It is clearly difficult to spot the 247 and 1016 clusters shown in Figures 1 and 2!

In reality the observational situation is better than it seems, mainly because the cluster LF is significantly “brighter” than that of the field: The so-called matched filter technique (Postman et al. 1996) as implemented by the EIS team (Olsen et al. 1999) is routinely used to detect clusters up to  $z \approx 1.3$ , with tentative analysis of followup observations strongly supporting a cluster at  $z \sim 1.2$  (L. Olsen, private communication).

### 2.2. X-rays

Turning to X-ray detection of clusters we show in Figure 4 the expected number of clusters per redshift bin (0.1 in  $z$ ) in the  $64 \text{ deg}^2$  XMM-LSS field brighter than the nominal flux detection limit of XMM. The figure is based on N-body simulations of a range of cosmologies, the conventional temperature–mass ( $T_X - M$ ) relation and a non-evolving (present-day) luminosity–temperature ( $L_X - T_X$ ) relation. It is clear from the figure how one can distinguish between  $\Lambda$  (flat, with low  $\Omega_M$ ), open and  $\Omega_M = 1$  cosmologies from observations in the range  $0.3 \lesssim$

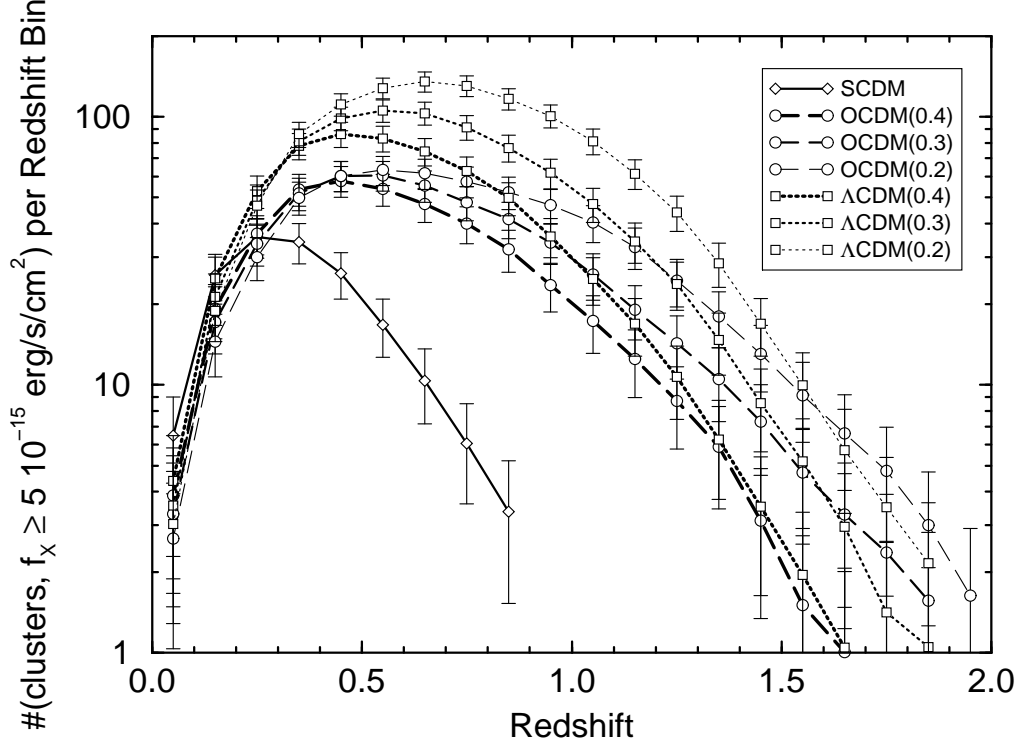


Figure 4. Differential number count  $dN/dz$  of X-ray clusters, brighter than the nominal XMM-Newton flux detection limit, expected in the 64 deg<sup>2</sup> XMM-LSS field for various cosmologies.

$z \lesssim 0.8$  and how one can furthermore determine the actual value of  $\Omega_M$  by adding observations in the range  $1 \lesssim z \lesssim 2$ . Though the theoretical predictions obviously depends on the above assumptions, one should note that the dependence of the  $L_X - T_X$  and  $T_X - M$  relations on redshift will be observationally well constrained in the future. Clusters have been detected in X-rays up to a current record redshift of  $z = 1.79$  (Fabian et al. 2001).

### 2.3. Thermal Sunyaev-Zeldovich effect

When CMB photons pass through the hot gas in a galaxy cluster they inverse Compton scatter off hot electrons in the gas shifting the CMB spectrum to slightly larger energies. This causes a CMB temperature *decrease* in the low frequency (Rayleigh-Jeans) part of the CMB spectrum of  $\Delta T/T_0 \simeq -2y$ , where  $T_0 = 2.73$  K and  $y$  is given by

$$y = \frac{k_B \sigma_T}{m_e c^2} \int n_e(l) T_e(l) dl \quad , \quad (1)$$

where  $\sigma_T$  the Thomson cross section,  $n_e$  the electron number density,  $T_e$  the electron temperature and the integral is along the line-of-sight.

Cluster detection through the tSZ effect offers two great advantages over X-ray detection: a) The tSZ properties of clusters are differently sensitive to

the structure of the intracluster medium than their X-ray properties because the local contribution to the tSZ effect is proportional to the pressure (eq. 1) whereas the local X-ray emissivity is proportional to the square of the density times the square root of the temperature (to first order). The tSZ effect is thus less centrally concentrated than the X-ray emission and much less sensitive to small-scale gas clumping. Moreover, the tSZ “luminosity” is proportional to the total thermal energy content of the cluster gas (eq. 1) which should correlate fairly tightly with the total baryon content of the cluster and hence its total mass. So the “ $L_{SZ} - M$ ” relation would be expected to be significantly tighter than the  $L_X - M$  relation. b) The tSZ “surface brightness” of a cluster is independent of its distance whereas its X-ray (and optical/NIR) surface brightness drops as  $(1+z)^4$ , so that very distant clusters are comparatively easier to detect through the tSZ effect.

The Planck survey will be all sky (except for excluded regions near the Galactic plane) and should detect  $\sim 10^4$  clusters at  $z \gtrsim 0.3$ ,  $\sim 10^3$  clusters at  $z \gtrsim 1$  and  $\sim 10^2$  clusters at  $z \gtrsim 1.5$ , depending on the cosmology, of course - the numbers given are for a  $(\Omega_M, \Omega_\Lambda) \sim (0.3, 0.7)$  Universe.

We finally note that combination of tSZ and X-ray data offers a powerful probe of the gas structure in clusters and in some circumstances may allow a direct determination of their individual distances and hence the Hubble parameter (Silk & White 1978).

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